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ORIGINAL ARTICLE

Achieving the 1.5 °C goal with equitable mitigation in Latin American countries

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Abstract
During the past years, the impact of climate change in Latin America has become more evident. It is affecting its natural resources and delaying sustainable development. Achieving the 1.5 °C long-term temperature goal of the Paris Agreement while ensuring the right to sustainable development is of particular interest to regions with high vulnerability and low adaptation capacity for climate change, such as Latin America. This article analyzes whether the Nationally Determined Contributions (NDCs) submitted within the Paris Agreement framework by Latin American countries align with achieving the 1.5 °C goal. For this analysis, the global carbon budget from 2020 onwards, compatible with the 1.5 °C global temperature scenario, is distributed among countries using two dimensions of equity (equality and historical responsibility). Then, the carbon budget allocated to Latin American countries is compared with the cumulative emissions implied in two scenarios. The first one is the NDC scenario that assumes the implementation of the NDCs submitted until December 31, 2022. The second scenario adds the goal of ending deforestation by 2030, signed by several countries of this region in the Global Leaders Declaration on Forest. Two main conclusions are obtained from the analysis of the cited scenarios. First, Latin American countries will consume 77% of their carbon budget in 2030 by implementing their NDCs. Second, this percentage could be reduced to 58% if Latin American countries reach zero emissions from the Land Use, Land Use Change, and Forestry sector by 2030. If achieved, the region would be on track to reach the 1.5 °C global goal.

Keywords Latin America · Paris Agreement · NDC · Mitigation · Carbon budget · Equity

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1 Introduction

Latin America is highly exposed, vulnerable, and impacted by climate change. In this region, the impacts are magnified by inequalities, poverty, and land use changes mainly due to deforestation, which implies loss of biodiversity and soil degradation. Also, changes in the precipitation patterns and extreme temperatures are impacting agriculture production (Barcena et al. 2020; IPCC 2022a).

In addition, future climate projections for Latin America suggest temperature increases and changes in precipitation will intensify the already existing vulnerabilities in this region. It is expected that due to droughts and shrinking glaciers, the region's risk of food and water insecurity will be accentuated. Also, there is an increasing risk for people and infrastructure caused by floods and landslides and the risk to human health related to the intensification of epidemics. Some of them are interlinked risks that could surpass the public service systems (Reyer et al. 2017; Nagy et al. 2018; IPCC 2022a).

For all the reasons mentioned above, countries must undertake adaptation and mitigation efforts to combat climate change and promote cooperation strategies within Latin America and in the framework of the multilateral climate agenda, the Paris Agreement (PA).

The PA, adopted in 2015, is the multilateral agreement for climate change governance. It establishes the goal of maintaining the average temperature increase well below 2 °C and pursuing efforts to limit this increase to 1.5 °C relative to preindustrial levels (United Nations 2015). According to the IPCC's Working Group III contribution to the Sixth Assessment Report (AR6), in scenarios that limit global warming to 1.5 °C, anthropogenic net GHG emissions must be reduced by 43% by 2030 relative to the 2019 level (IPCC 2022b). In addition, according to Working Group I, limiting global warming to 1.5 °C requires maintaining the cumulative CO_2 emissions, until reaching net-zero CO_2, below the remaining global carbon budget (RGCB), which is only 400 $GtCO_2$ from 2020 onwards (67% likelihood) (IPCC 2021).

The Nationally Determined Contributions (NDCs) are the PA's cornerstone for achieving the long-term temperature goal. In a five-year cycle, at maximum, countries communicate mitigation commitments in their NDC that will contribute to achieving the PA's goals. Regarding the current NDCs, the result of the Synthesis Report published by the UNFCCC Secretariat in October 2022 is of concern. This report assesses the aggregated effect of the 166 latest available NDCs. These include the NDCs submitted by all Parties to the PA as of September 23, 2022. The report confirms that total global GHG emission levels, considering the implementation of the NDCs, are estimated to be 0.6% lower in 2030 than in 2019. Based on the latest NDCs, the same report states that cumulative CO_2 emissions in 2020–2030 would likely amount to 430 $GtCO_2$ (UNFCCC 2022a). Thus, the RGCB compatible with the 1.5 °C goal (67% of likelihood) will be exhausted by 2030.

Observing the gap between the current mitigation commitments and the 1.5 °C goal mentioned above, it is urgent to perform an analysis that contributes to closing this gap (den Elzen et al. 2022). Besides, we should keep in mind that Article 2 of the PA sets out its implementation to reflect equity and the principle of "common but differentiated responsibilities and respective capabilities" (CBDR&RC). And also, Article 4 establishes that the long-term temperature goal has to be achieved based on equity and in the context of sustainable development, including efforts to eradicate poverty. According to Article 4, subsequent NDCs must reflect the highest possible ambition under the CBDR&RC principle (United Nations 2015).

Equity permeates the PA and is deeply rooted in the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations 1992). Despite this, a consensus on how to operationalize equity in climate change mitigation has never been attained within the UNFCCC. Mattoo and Subramanian (2012) review on Equity and Climate Change highlights four dimensions for applying equity in mitigation. These dimensions are also included in the AR5 and are as follows: equality, operationalized by allocating the same emissions per capita, based on the idea that all the planet's inhabitants have the same rights; historical responsibility, based on the necessity to compensate for the harm caused to others; capacity, based on the ability to pay to undertake mitigation actions; and the preservation of the right to sustainable development (IPCC 2014).

We differentiate two main approaches among the models that aim to operationalize the equity dimensions mentioned above. One approach is that of models that aim to distribute emissions reduction efforts among countries (Winkler and Marquard 2012). In this group, we find the Greenhouse Development Rights framework (Baer et al. 2008) and the Climate Equity Reference Framework (Holz et al. 2019). These models distribute the burden of emissions reductions and adaptation to climate change by assessing capacity and responsibility. It is worth noting the analysis by Robiou Du Pont et al. (2017) in which cost-optimal mitigation scenarios are represented based on different equity dimensions.

A different approach includes models that distribute the RGCB or the right to future emissions based on equity instead of distributing emissions reductions. In this group, we find analyses from the (German Advisory Council on Global Change 2009; Kanitkar et al. 2013; Raupach et al. 2014; Gignac and Matthews 2015; Alcaraz et al. 2018). Raupach's model allows weighting the result of an equal distribution of the RGCB with a distribution based on the current emissions level (following the inertia principle). Models by the German Advisory Council on Global Change, Kanitkar, Gignac, and Alcaraz are based on the principle of equality and they consider the differentiated historical responsibility of countries.

Considerations of the date to begin historical responsibility are also debatable (Neumayer 2000; Müller et al. 2009; Höhne et al. 2011). Some authors sustain that historical responsibility should be considered starting from the beginning of the industrial revolution. Moreover, taking into account the industrialization process, with its consequent associated emissions, allowed the development of several countries and their current population to enjoy greater levels of well-being (Cao 2008; Kanitkar et al. 2013). Some authors consider that the international community was only fully aware of the climate change threat until the beginning of the 1990s (Baer et al. 2008; German Advisory Council on Global Change 2009; Parikh and Parikh 2009). In 1990, the IPCC published its first assessment report, and from that moment started the work that led to the approval and subsequent ratification of the UNFCCC document. When the UNFCCC entered into force, no state could claim ignorance of the damage of greenhouse gas emissions and, therefore, could not evade their responsibility. It is worth mentioning that some authors highlight the unequal historical responsibility of countries and the need to concede carbon space to countries with more challenges in terms of development needs (Winkler et al. 2013; Bruckner et al. 2022), among which we observe Latin American and Caribbean countries.

All Latin American (LATAM) countries have presented their first NDC and an updated or reviewed version of their first NDC (except for Guyana) (UNFCCC 2022b). Considering LATAM countries demonstrated political will to address climate change and their current development needs, the analysis of this region under the prism of equity is deemed of particular interest to policy-makers.

Recent research is tracking the progress of countries' climate policies. These include LATAM countries and the compatibility in their NDC to achieve the PA's long-term goals (Robiou Du Pont et al. 2017; Kemp-Benedict et al. 2018; CAT 2022; MSSRF 2022). Nevertheless, we observe a lack of research considering all LATAM countries and integrating a regional analysis. This article aims to analyze if LATAM countries updated NDC are fair and ambitious in a mitigation scenario compatible with the 1.5 °C global temperature goal. The Model of Climate Justice (MCJ) (Alcaraz et al. 2018) will be used for the analysis. The model applies equity criteria to allocate future cumulative CO_2 emissions compatible with the 1.5 °C long-term temperature goal. In other words, the MCJ allows us to determine the carbon budget that would be available for Latin America at a country and regional level. We then compare the estimated available carbon budget for LATAM countries with the share of their budget consumed within their first submitted NDC. This analysis will allow us to evaluate LATAM countries based on their present circumstances.

2 Methodology

2.1 Studied countries

The article analyzes 20 countries from Latin America, excluding the Caribbean region. These countries include Mexico and countries from the Central and South American subregions (United Nations classification) (UNDESA 2022).

Table 1 shows the emissions profile and several development indicators from LATAM countries included in this analysis. The historical CO_2 emissions data is obtained from the Climate Watch dataset (Climate Watch 2022). It is essential to highlight that according to the information complementing the database, emissions from the Land Use, Land Use Change, and Forestry (LULUCF) sector present a high uncertainty, between 50 and 70%. In contrast, the uncertainty from data excluding LULUCF is lesser, approximately 8%. Uncertainties related to LULUCF data are widely acknowledged and it is necessary to reduce them (Gütschow et al. 2021; McGlynn et al. 2022; Friedlingstein et al. 2022).

Regarding LATAM CO_2 emissions, excluding LULUCF, the cumulative per capita emissions from 1990 to 2019 and for 2019 are below the world average. In contrast, these numbers drastically change when we include LULUCF emissions. In this case, aggregated LATAM emissions are above the world average. For several LATAM countries (Belize, Bolivia, Brazil, Guyana, Nicaragua, Peru, Paraguay, and Suriname), the LULUCF sector represents more than 2/3 of their total CO_2 emissions. A relevant exception is Uruguay, which has negative cumulative emissions per capita from 1990 to 2019, including LULUCF.

Although the region has many similarities, significant differences are observable in their development indicators. LATAM countries classified by the World Bank as lower-middle income (World Bank 2022a), such as Bolivia, El Salvador, Honduras, and Nicaragua, and some upper-middle income countries such as Guatemala and Belize, have considerably low GDP (PPP) per capita than the rest of them. They all have a GDP (PPP) per capita below 10,000 USD, which is lower than the world average (17,587 USD).

Table 1 also presents development indicators that give a more comprehensive picture of the region. It is evident that some countries in the region have development needs. The following should be highlighted: El Salvador, Guatemala, Honduras, and Nicaragua have a Human Development Index (HDI) below 0.7; and Belize, Guyana, Honduras,

Table 1 Indicators from Latin American countries and development indicators, Latin American total, and world aggregate. Population data from UNDESA (UNDESA 2022), emissions from the Climate Watch dataset (Climate Watch 2022), GDP from World Bank (World Bank 2023). Poverty headcount ratio at US$2.15 a day and Gini Index from World Bank (World Bank 2020, 2022a); Human Development Index from (UNEP 2020)

	Population (2019)	Cumulative CO_2 em. including LULUCF per capita (1990–2019)	Cumulative CO_2 em. excluding LULUCF per capita (1990–2019)	CO_2 em. excluding LULUCF per capita (2019)	GDP (PPP) per capita (2019)	Poverty headcount ratio at US$2.15 a day (2017 PPP) (2019*)	Human Development Index (2019)	Gini Index (2019*)
	Millions	tCO_2	tCO_2	tCO_2	USD	(% of pop.)		
Argentina	44.6	5.4	3.8	3.8	23,187	0.8	0.85	42.9
Belize	0.4	20.5	2.0	1.7	9491	18.0	0.71	53.3
Bolivia	11.7	8.5	1.4	1.9	8947	1.9	0.72	41.6
Brazil	211.0	6.5	1.9	2.1	15,362	5.4	0.77	53.5
Chile	18.9	1.2	3.7	4.8	25,430	0.7	0.86	44.9
Colombia	49.8	3.5	1.5	1.6	15,856	5.3	0.77	51.3
Costa Rica	5.1	1.1	1.5	1.6	22,560	1.1	0.82	48.2
Ecuador	17.2	4.3	2.1	2.3	11,970	3.6	0.76	45.7
El Salvador	6.3	1.2	1.0	1.2	9403	1.4	0.68	38.8
Guatemala	17.0	1.8	0.8	1.1	8837	9.5	0.64	48.3
Guyana	0.8	16.0	2.3	3.5	13,247	11.9	0.71	45.1
Honduras	9.9	1.7	0.9	1.0	5900	12.7	0.63	48.2
Mexico	124.6	3.8	3.9	3.6	20,337	3.1	0.78	45.4
Nicaragua	6.6	4.3	0.7	0.8	5613	3.9	0.66	46.2
Panama	4.2	3.7	2.2	3.2	33,133	1.0	0.82	49.8
Paraguay	6.5	10.5	0.9	1.3	14,278	1.0	0.73	45.7
Peru	32.6	3.9	1.3	1.7	13,381	3.0	0.78	41.6
Suriname	0.6	14.1	3.9	4.4	19,341	18.4	0.75	57.9
Uruguay	3.4	− 1.1	1.8	1.9	24,237	0.1	0.82	39.7
Venezuela	29.3	9.4	5.3	3.8	17,273 **	7.1	0.72	44.8

Table 1 (continued)

	Population (2019)	Cumulative CO_2 em. including LULUCF per capita (1990–2019)	Cumulative CO_2 em. excluding LULUCF per capita (1990–2019)	CO_2 em. excluding LULUCF per capita (2019)	GDP (PPP) per capita (2019)	Poverty headcount ratio at US$2.15 a day (2017 PPP) (2019*)	Human Development Index (2019)	Gini Index (2019*)
	Millions	tCO_2	tCO_2	tCO_2	USD	(% of pop.)		
Latin America	**600.3**	**5.1**	**2.5**	**2.6**	**18,808**	**4.3**	**0.77**	
World	**7703**	**4.5**	**4.3**	**4.6**	**17,587**	**8.4**	**0.74**	

To avoid missing data from 2019, data from the last year available is used: *Belize (1999); Chile (2020); Guatemala (2014); Guyana (1998); Mexico (2020); Nicaragua (2014); Suriname (1999); Venezuela (2006). **Venezuela (2011)

and Suriname are countries where more than 10% of their population lives with less than US$2.15 a day. Similarly, it is also important to note that in most of these countries, the income distribution inequality based on the Gini index is higher than 40, excepting El Salvador and Uruguay. This fact indicates concerning levels of inequality in Latin America; the top 10% captures 55% of national income (Chancel et al. 2022).

There are other interesting observations from the analyzed development indicators. Suriname has a GDP (PPP) per capita above the world average; however, with 18.4%, it has the highest population living on US$2.15 a day in the region. Some countries have similar GDP (PPP) per capita levels, for example, Belize and Bolivia, with different percentages of their population living with less than US$2.15, 18% and 1.9%, respectively.

2.2 The model of climate justice

In this research, the Model of Climate Justice (MCJ) is used to distribute the global carbon budget compatible with the 1.5 °C goal (400 $GtCO_2$ with 67% likelihood) available from 2020 onwards among countries (Alcaraz et al. 2018). The global scenario considered is the WITCH-GLOBIOM 4.4 CD-LINKS_NPi2020_400 World Emissions|CO2 published in the AR6 Scenarios Database (Byers et al. 2022). This scenario is compatible with a global emissions scenario limiting temperature increase to 1.5 °C with respect to preindustrial temperature with no or limited overshoot. Additionally, for the inputs to the MCJ, CO_2 historical emissions data are obtained from the Climate Watch dataset (Climate Watch 2022). The historical population and prospects data were retrieved from the UNDESA medium variant scenario (UNDESA 2022).

The global carbon budget is distributed using the MCJ, considering equality and historical responsibility dimensions. It allocates the same level of emissions per capita for all countries. Then, it corrects the allocation taking into account countries' historical responsibility. The period used for historical responsibility is from 1990 to 2019, the available period in the dataset. The resulting distribution allocates more emissions to countries with emissions per capita below the world average and vice versa. For further insights into the mathematical details of the MCJ, the authors recommend reading Annex I contained in the supplementary electronic material of the O. Alcaraz et al. (2018) article.

The results obtained are the net CO_2 emissions allocations for LATAM countries from 2020 onwards. In other words, this is the carbon budget that would be available for each country from 2020. Once we have obtained the carbon budget allocations, we compare the results with two scenarios:

- NDC scenario (NDC). Attending to the mitigation commitments stated in the NDC, we trace a mitigation pathway between 2020 and 2030 for CO_2 emissions, including LULUCF. Next, we estimate the cumulative emissions implied by this pathway for the 2020–2030 period.
- NDC with Glasgow Leaders' Declaration on Forests and Land Use scenario (NDC w GLDF). This scenario is constructed considering compliance with the objectives of the Glasgow Leaders' Declaration on Forests and Land Use (UK-COP26 2021). These objectives include "working collectively to halt and reverse forest loss and land degradation by 2030." All LATAM countries have signed the abovementioned Declaration except Bolivia and Venezuela. For countries that have signed the Declaration with positive LULUCF emissions, a linear mitigation pathway for LULUCF CO_2 emissions that lead to zero in 2030 has been traced. While for CO_2 emissions excluding LULUCF,

a mitigation pathway has been assumed until 2030, applying the emission reductions provided in the NDC. Finally, we calculate the sum of the cumulative emissions between 2020 and 2030 that both pathways imply. For Bolivia, Venezuela, and countries in the Declaration with negative emissions for the LULUCF sector (Chile, Costa Rica, and Uruguay), the NDC scenario's cumulative emissions are maintained.

2.3 The NDCs

The updated and submitted NDC by LATAM countries until December 2022 are considered for analysis in this article (UNFCCC 2022b). By December 31, 2022, eighteen LATAM countries had submitted their updated NDC or their second NDC, complying with the provisions in paragraphs 23 and 24 of decision 1/cp.21 (UNFCCC 2015).

Table 2 summarizes the mitigation targets and information submitted within LATAM countries' NDC. Although several countries present conditional targets that depend on external climate finance, only unconditional targets are considered for this article. Estimating the cumulative emission that each country's NDC implies for the 2020–2030 period requires knowing in advance the estimated value of their emissions level in 2030.

Table 2 Information about the Latin American countries' NDCs (UNFCCC 2022b) and, in the last column, the projection of the emissions in 2030 according to the authors

	Reference indicator	Reference year	Target in 2030	Emission target in 2030 ($MtCO_2$)
Argentina	Absolute goal target		359 $MtCO_2$	198
Belize	Non-quantifiable			5.3
Bolivia	Non-quantifiable			111
Brazil	Base year	2005	− 50.0%	716
Chile	Cumulative emissions		1100 $MtCO_2eq$	24
Colombia	BAU	2015	− 51.0%	99
Costa Rica	Absolute goal target		9.11 $MtCO_2eq$	0.1
Ecuador	BAU	2010	− 9.0% *	93
El Salvador	BAU	2016	− 39.0%	4.4
Guatemala	BAU	2017	− 11.2%	20
Guyana	Non-quantifiable			19
Honduras	BAU	2012	− 16.0%	19
Mexico	BAU	2013	− 35.0%	445
Nicaragua	Non-quantifiable			43
Panama	Non-quantifiable			23
Paraguay	BAU	2014	− 10.0%	92
Peru	BAU	2010	− 30.0%	134
Suriname	Non-quantifiable			11
Uruguay	Absolute goal target	2019	9.267 $MtCO_2$	6.4
Venezuela	BAU	2012	**	461

Note: *Ecuador presents 2025 targets instead of 2030. **Venezuela's NDC is fully conditional to international support, so no reduction objective is presented

It should be noted that, unlike other countries, the updated Chilean NDC presents a commitment based on cumulative emissions for 2020–2030 and a reduction target to be achieved by 2030. In addition to submitting an absolute target for 2030, Costa Rica also presented its commitment for cumulative emissions between 2021 and 2030. We consider this type of commitment more robust than those based on a target year since it offers information about the country's overall projected emissions to be released into the atmosphere. Therefore, the temperature increase produced by such emissions can be estimated more accurately (Matthews et al. 2020).

The calculation method for the resulting emissions in 2030 for each NDC depends on the country's type of commitment. Note that emissions estimations are calculated for CO_2 emissions. At the same time, the majority of the studied NDC present their objectives for all GHG. The 2030 emissions target in Table 2 is estimated assuming the same reduction applied to CO_2 emissions. El Salvador, Uruguay, and Venezuela present their emission target for CO_2, so that assumption is not needed in those cases.

- For those countries presenting a target as a percentage reduction from a base year, 2030 emissions are calculated by applying the reduction directly to the historical emissions from the base year.
- For countries with an absolute emission reduction target, emissions reductions are determined based on the historical data presented in the NDC and then applied to the historical emissions from the Climate Watch dataset. Note that this may lead to different emissions values for 2030 than those presented as a target in the NDC.
- For countries with targets based on a business as usual (BAU) scenario, the slopes of the NDC-supplied BAU scenario are applied to the historical Climate Watch dataset and then the reduction target in the NDC is applied to the year 2030 of this scenario.
- For those cases in which the NDC does not present a quantifiable emissions reduction target, a linear trend scenario is calculated based on their historical data.

After estimating target emissions for 2030 from each country, a linear trajectory between 2019 (the last year of historical data) and 2030 is assumed. For countries considering an emission reduction target for 2025, the emissions level at 2025 is estimated according to their target type. Therefore, to determine the emissions in 2030, a linear trend between 2019 and 2025 is projected. The emissions trajectory between 2019 and 2025 was assumed to continue at the same rate after 2025 until 2030. Finally, the cumulative emissions are calculated by adding up all the emissions between 2020 and 2030.

It should be noted that since 2019 is the last year of historical emissions used, the effect that COVID-19 had on emissions will not be reflected in this study. The calculated cumulative emissions according to the NDCs will likely to be overestimated because the actual 2020 and 2021 emissions will be lower than the estimated levels in this analysis.

3 Results and discussion

3.1 Cumulative emissions allocated by the MCJ to LATAM countries

Figure 1 compares the historical cumulative CO_2 emissions, including LULUCF, with the remaining carbon budget allocated using the MCJ that considers equality

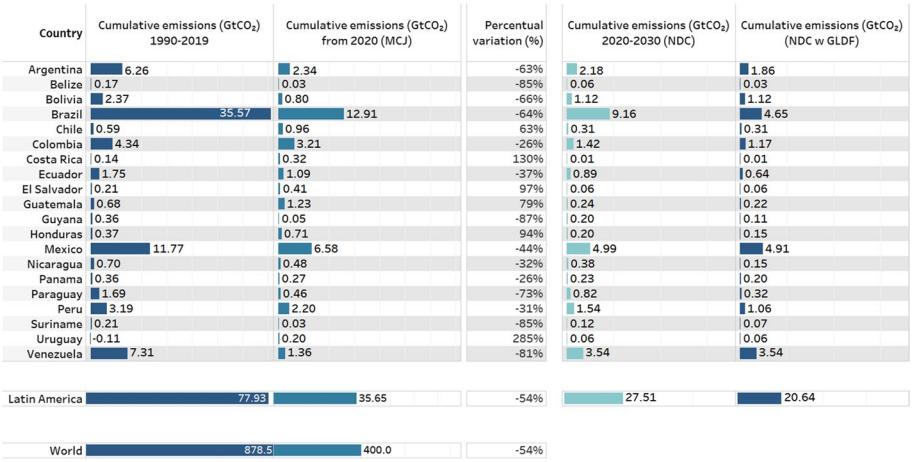

Fig. 1 Cumulative CO_2 emissions including LULUCF. The first column shows the carbon budget consumed in the historical period 1990–2019; the second column shows the remaining carbon budget allocated according to the MCJ from 2020 onwards. The third column is the resulting percentage variation between historical and future allocated emissions. The fourth column indicates the cumulative emissions implied in the countries' NDC for the 2020–2030 period. The fifth column represents the cumulative emissions that the "NDC w GLDF" scenario implies

and historical responsibility from 1990. This allocation is compatible with the 1.5 °C mitigation scenario (> 66%) that implies a remaining global carbon budget from 2020 onwards of 400 $GtCO_2$.

The carbon budget that would be available from 2020 onwards to the LATAM countries group according to the results obtained with the MCJ amounts to 35.65 $GtCO_2$ (see Fig. 1). This figure represents 8.9% of the remaining global carbon budget, 54% less than the emitted in the analyzed historical period 1990–2019. This 54% reduction coincides with the percentage reduction that should be taken globally.

The results obtained with the MCJ present two important limitations. The first one is related to the mentioned uncertainties associated with the LULUCF sector, which is also LATAM countries' most critical emissions sector. The mentioned uncertainties cannot be overcome until there is a unification of the diverse methodologies used in the inventories for LULUCF (McGlynn et al. 2022). The second limitation is related to the fact that the MCJ does not include the capacity and the right to development dimensions. Although regional development indicators do not differ excessively from the world average, significant differences between countries will be discussed in this section.

Considering that mitigation scenarios compatible with the 1.5 °C situate CO_2 emissions neutrality towards 2050 and that the regional remaining carbon budget is 35.65 $GtCO_2$, estimating a rough average, available annual emissions for Latin America would be 1.74 $GtCO_2$/year from 2020 to 2050. For many regions, achieving this reduction implies making critical structural changes in all economic sectors, and in the case of Latin America, changes in land and extensive forest masses management.

Figure 1 also compares historical cumulative CO_2 emissions, including LULUCF, with the remaining carbon budget allocated using the MCJ for every LATAM country. We can observe significant differences between countries. Achieving the 1.5 °C target worldwide requires a 54% lower carbon budget from 2020 onwards than historical emissions from

1990 to 2019. Considering this fact, we will use this value to discuss the allocated carbon budget for every country. We have identified three groups of countries:

- Countries with a remaining carbon budget reduced by 54% or more compared to their historical cumulative emissions are Argentina, Belize, Bolivia, Brazil, Guyana, Paraguay, Suriname, and Venezuela. They all had historical CO_2 emissions per capita, including LULUCF, higher than the world and LATAM average (see Table 1). Therefore, their future mitigation efforts should be higher than the global average. In this group, we find two profiles that are differentiated clearly.

    - Countries with LULUCF sector emissions that amount to more than 2/3 of their total emissions. This group has six countries: Belize, Bolivia, Brazil, Guyana, Paraguay, and Suriname. Among these countries, Bolivia, classified as a lower middle-income country, has only 25% of its rural population with access to safe drinking water (FAO 2021). The rest of the countries in this group are classified by the World Bank as upper–middle-income countries (World Bank 2022b). Brazil is the most populated country in the region and has the first place in LULUCF emissions worldwide. Although Brazil's HDI is higher than the world average and equal to the LATAM average, its poverty ratio is lower than the world and LATAM averages; according to its 53.3 Gini coefficient (Table 1), it is the second country with the highest inequalities. Belize and Guyana are countries with high percentages of people living below the poverty line. Belize also has high inequality levels. For this group of countries, it should be a priority to achieve the well-being of its people by providing them with basic infrastructure for development.
    - On the other hand, we observe Argentina and Venezuela, two countries with CO_2 emissions per capita (excluding LULUCF) above the LATAM average. It is important to remark that Argentina has good results for its development indicators. Argentina's HDI is 0.85, one of the highest in the region, only preceded by Chile with 0.86. At the same time, Argentina has lower levels of inequality than other countries in the region, as reflected by its Gini coefficient (see Table 1). Venezuela deserves a separate comment; it has the highest cumulative CO_2 emissions per capita, excluding LULUCF, in the region. Ninety-eight percent of these emissions are produced by their energy sector and are closely related to oil extraction (Climate Watch 2022). In 2013, fuel exports represented 98% of the total Venezuelan exports, contributing to 24% of their GDP (ECLAC 2022; World Bank 2022c). Venezuela still has significant challenges in reducing poverty rates.

- Countries that should face the future with a lower remaining carbon budget than those from their 1990–2019 historical period but require lower reductions than the − 54% world average. The countries in this group are Colombia, Ecuador, Mexico, Nicaragua, Panama, and Peru.

    - In this group, we observe four countries (Colombia, Ecuador, Nicaragua, and Peru) with emissions from their LULUCF sector representing over 50% of their CO_2 emissions. These countries also have a GDP per capita lower than the world average. Since the GDP per capita of these countries is relatively low, this data supports the idea that deforestation does not necessarily contributes to economic well-being (Tritsch and Arvor 2016).

- Mexico and Panama are also included in this group. Both countries have a GDP per capita above the world average. Emissions for the LULUCF sector in Panama are significant (41% of their total emissions), it has the highest GDP per capita in the region, and its HDI is higher than 0.8. However, it is essential to note that inequalities in this country are substantial (Gini 49.8). In Mexico, 92% of their emissions come from the energy sector that, like Venezuela, is based on fossil fuels (Climate Watch 2022).

- Countries that could face the future with a carbon budget from 2020 onwards higher than their historical cumulative emissions (1990–2019). This group includes 6 of the 20 analyzed countries (Chile, Costa Rica, El Salvador, Guatemala, Honduras, and Uruguay).

  - Chile, Costa Rica, and Uruguay have good development indicators, and their cumulative emission per capita (including LULUCF) are the lowest in the region. In the case of Uruguay, LULUCF emissions are negative. These countries' low CO_2 emissions can be explained due to their negative LULUCF emissions that partially offset, or like in the case of Uruguay, totally offset CO_2 emissions from other sectors.
  - El Salvador, Guatemala, and Honduras have an HDI below 0.7 and a GDP per capita below the world average. These countries still have important development challenges. 50% of the population in Guatemala and Honduras lack access to clean fuels and technologies for cooking (Global Health Observatory 2022). While energy coverage in rural communities only reaches 85% of its population (World Bank 2021). In El Salvador, Guatemala, and Honduras, the portion of the rural population with access to basic drinking water services only reaches 86.5%, 86.8%, and 83.8%, respectively (FAO 2021).

3.2 Analysis of the Latin American NDCs

This section describes the analysis of the cumulative emissions implied for the 2030 commitments from LATAM countries in their last updated NDC (scenario "NDC"). These cumulative emissions are compared with the total carbon budget (or cumulative CO_2 emissions including LULUCF) allocated with the MCJ from 2020 onwards in line with the 1.5 °C global temperature goal (Fig. 2). To complement this analysis, we compare the scenario "NDC" with the "NDC w GLDF" described in Sect. 2.2.

Before analyzing the carbon budget consumption for the 2020–2030 period, it is precise to consider the optimal percentage of this consumption. Globally, the scenarios compatible with the 1.5 °C (> 66%) set carbon neutrality in 2050; consequently, the global carbon budget that amounts to 400 $GtCO_2$ should last until 2050. Therefore, if we consider a linear reduction of the net global CO_2 emissions that reaches zero in 2050, the carbon budget that may be consumed in 2020–2030 should be 55% of the total. This 55% should be considered merely a useful reference for this analysis. However, it should be taken into account that several countries have enough carbon budget to delay a few years their emissions peak. These countries could consume more than 55% of their carbon budget and remain on the path for 1.5 °C.

Considering the cumulative emissions for the "NDC" and "NDC w GLDF" scenarios (Fig. 1), the percentage of the remaining carbon budget allocated to these countries that would be consumed in both scenarios can be seen in Fig. 2.

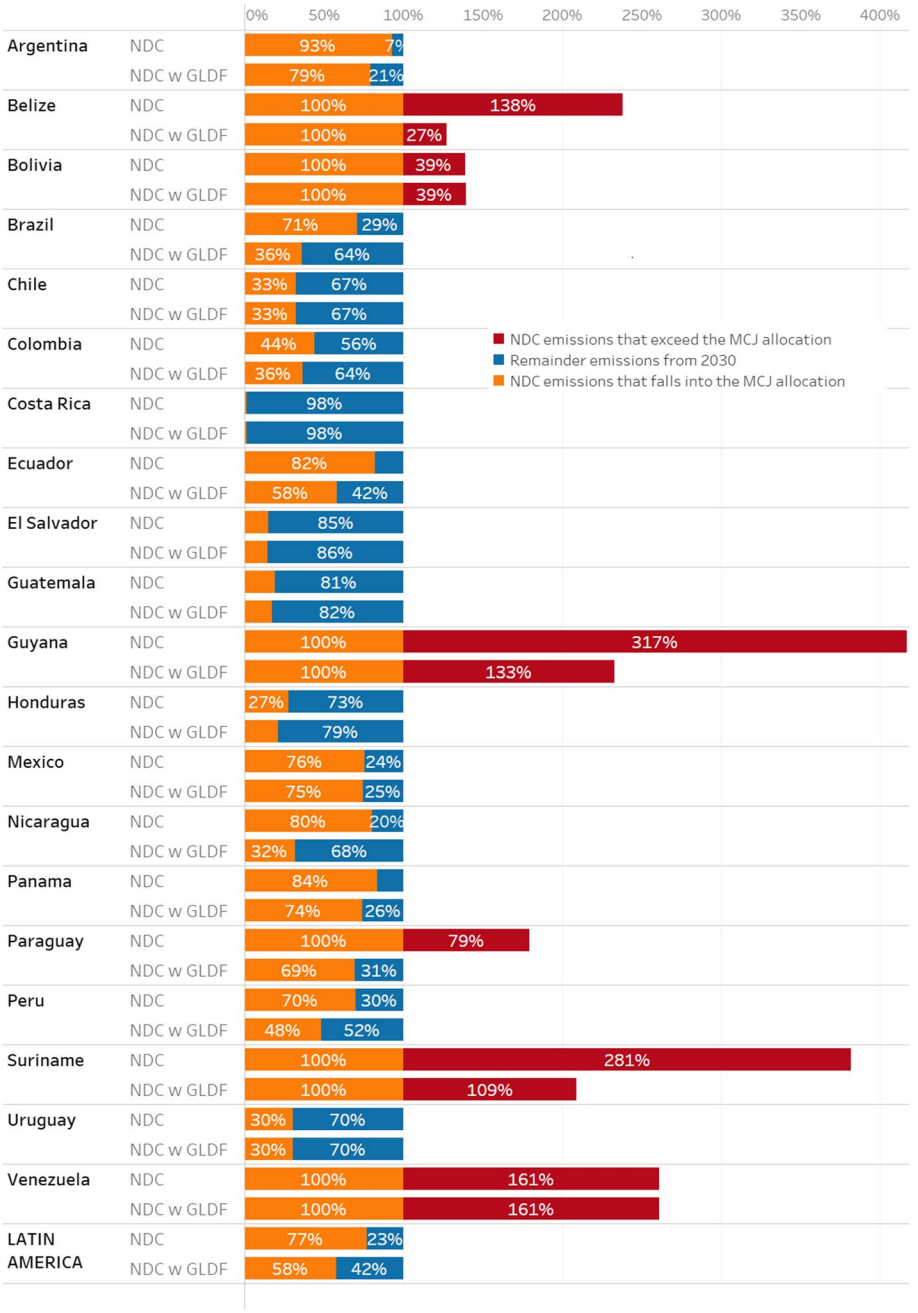

Fig. 2 Percentage of the carbon budget that, according to the scenarios "NDC" and "NDC w GLDF," could be emitted into the atmosphere in 2030 (orange + red bars) with respect to the carbon budget allocated by the MCJ from 2020 onwards. The orange bar indicates the percentage that falls within the allocation, and the red one indicates emissions that exceed the allocation. The blue bar indicates the percentage of emissions available for countries from 2030 onwards

In Fig. 2, we can observe a group of six countries consuming their total carbon budget allocated with the MCJ in 2030. These countries are Belize, Bolivia, Guyana, Paraguay, Suriname, and Venezuela. All these countries have significant LULUCF emissions that far exceed 2/3 of their CO_2 emissions, except for Venezuela where the LULUCF sector "only" reaches 44%. Even in the "NDC w GLDF" scenario, these countries (except Paraguay) do not manage to adjust to the allocated carbon budget. We should consider that the NDC from Belize, Bolivia, Guyana, and Suriname contain political actions they will undertake; however, they do not have quantifiable emissions reduction objectives. This lack of quantifiable objectives is why a BAU scenario has been traced for these countries until 2030. Consequently, it is expected that the implementation of the NDC will lead them to achieve future emissions reductions, which this analysis could not contemplate.

Cumulative emissions for 2020–2030 for all other countries are below their carbon budget, with different percentages of consumption ranging from 2% in the case of Costa Rica up to 93% in the case of Argentina. Considering the reference commented before of 55% consumption of the allocated carbon budget, we can divide the countries into two major groups.

- Countries that consume below 55% of their carbon budget in their first NDC: Chile, Colombia, Costa Rica, El Salvador, Guatemala, Honduras, and Uruguay. In this group, we observe Chile, Costa Rica, and Uruguay, where their LULUCF sector is responsible for important CO_2 removals and has relatively low emissions from other sectors. In this group, we can also observe El Salvador and Honduras, two of the poorest countries from the analyzed countries (both classified as lower-middle income), with the most significant development challenges in the region. Additionally, these countries have a high climate risk index, meaning they must make a great effort to adapt to the impacts of climate change that they already have (Eckstein et al. 2021). As a result, these countries will likely need and use their carbon budget during the following decades to provide their entire population with basic infrastructure. Such infrastructure includes access to electricity, drinkable water, clean cooking technologies, and achieve greater resilience to climate change impacts.
- Countries that consume between 55 and 100% of their carbon budget in their first NDC: Argentina, Brazil, Ecuador, Mexico, Nicaragua, Panama, and Peru. The "NDC w GLDF" scenario shows that achieving an end to deforestation would put Brazil, Ecuador, Nicaragua, and Peru very near or in line with the 1.5 °C global goal. On the other hand, Argentina, México, and Panama, three countries with a GDP per capita below the regional average, should increase the ambition in their NDC.

Beyond the results obtained for each country, which are subject to an important degree of uncertainty linked to the LULUCF sector uncertainties, it is interesting to assess countries at a regional level. At the regional level, it is worth mentioning that the aggregate commitments of LATAM countries will have consumed 77% of their total carbon budget by 2030. This percentage will decrease to 58% if the countries that signed the Glasgow Leaders' Declaration on Forests and Land Use achieve the objective of ending deforestation by 2030. In this case, LATAM countries could yet align with the long-term temperature goal of 1.5 °C.

As we have observed, LULUCF in Latin America has the most CO_2 contribution (50% of the total regional CO_2 emissions) and offers the most significant emissions reduction potential. According to the AR6, LULUCF emissions are easily abatable since there are multiple mitigation options based on the land, such as reforestation, forest, and natural

ecosystems preservation. This option has multiple synergies with the Sustainable Development Goals, such as improving the quality of life in rural populations and the opportunity to reduce the great inequalities that prevail in several LATAM countries (IPCC 2022c).

Even though forest conservation is globally very important, LATAM countries have been reluctant to acquire forest protection policies arguing in favor of sovereignty. International regulations represent an opportunity to rethink agricultural production and commercial practices. One example is the "Regulation on deforestation-free products," recently approved by the EU27, which prohibits importing and exporting raw materials associated with forest destruction. These regulations can also help LATAM countries to guide cooperation to build deforestation-free supply chains as a regional practice (European Commision 2021; Garcia and Pauwels 2022).

Some barriers that obstruct implementing mitigation measures in the LULUCF are well identified. One of these barriers is finance, since mitigation efforts depend on governmental sources that sometimes do not have sufficient investment capacity (IPCC 2022c). In this point, international cooperation initiatives that promote forest ecosystems protection and restoration by working closely with local communities and indigenous peoples are of special interest. The knowledge held by these communities is widely recognized as essential for addressing climate solutions and preserving ecosystemic services (Conservation International 2022; NICFI 2022).

In this context, according to the Sustainable Finance Index Report, there has not been a cost evaluation to implement LATAM NDCs, which makes it very difficult to determine whether the current financial flows are adequate. This report assesses the extent to which LATAM countries' multilateral, bilateral and public income is intended for climate change mitigation and adaptation (Guzmán and de la Fuente 2020).

3.3 Analysis of the CO_2 emissions and economic evolution for Latin America

The energy sector is the second greatest CO_2 emissions contributor in LATAM. In this region, some countries have CO_2 emissions per capita below the world average. Some of these countries have high levels of poverty, relatively low levels of HDI, and a high index of inequalities (Honduras and Nicaragua are especially relevant examples). It is in the context of a region that must address development needs when it is necessary to question to what extent it is reasonable to expect the LATAM region reaches its peak emission in the following years.

Various studies relate the evolution of energy consumption over time (with the emission from this sector) with countries' development stages and economic evolution. In the first stage of economic development, CO_2 per capita emissions grow linearly with the economy. In the second stage, the impact of the economy on environmental degradation is reduced. Finally, in the third stage, the environmental impact and CO_2 per capita emissions decrease as the GDP per capita grows. This occurs when countries can invest in research and development and start substituting old technologies for newer, cleaner, and more efficient ones (Robalino-López et al. 2015; Wang and Li 2021).

Figure 3 compares the world and LATAM CO_2 emissions excluding LULUCF per capita evolution as a function of the GDP per capita. It is worth noting the difference between the world and Latin America's per capita emissions and the slower growth rate of GDP per capita in Latin America compared to the world average. While worldwide, during the last decade, there has been a tendency to decouple economic growth and emissions, this trend is not observed clearly yet in the LATAM curve, which has a positive slope with a

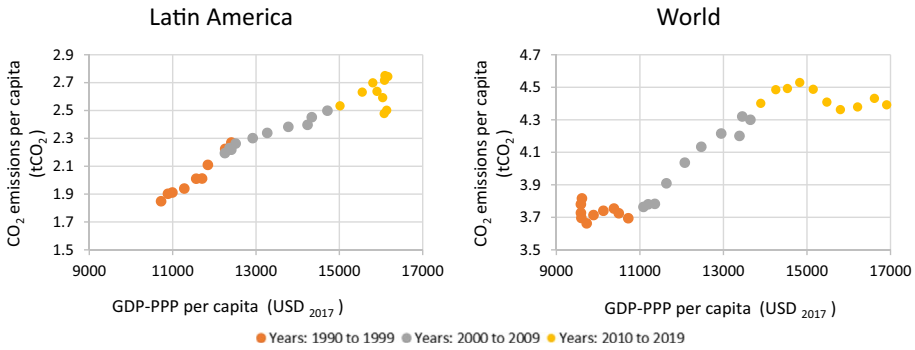

Fig. 3 Evolution of CO_2 emissions excluding LULUCF and GDP per capita for the LATAM region compared with the world evolution

decrease of emissions during the last years that is not accompanied of GDP growth but by its stagnation. Decoupling CO_2 per capita and GDP per capita is key to building development trajectories compatible with the ambitious 1.5 °C goal. Some recommendations to accomplish this are as follows: promoting technological innovations and energy efficiency that would help reduce energy intensity; implementing renewable energy technologies that would reduce carbon intensity; and promoting low-emissions lifestyles by increasing public awareness around energy and emissions savings (Chen et al. 2018; Yao et al. 2019).

4 Conclusions

Latin America faces the tremendous challenge of advancing along the path of sustainable development while overcoming the structural conditions that make it one of the regions in the world with the most inequalities. In addition, the highly climate-vulnerable region must face the impacts of climate change and promote climate resilience for its population. Latin America requires attending to development challenges while attending to their commitments within the PA's framework and contributing to achieving the 1.5 °C global temperature stabilization goal. According to the PA, this contribution should be made based on equity while promoting transparency and environmental integrity (United Nations 2015).

The scientific community warns that the 1.5 °C global temperature average stabilization scenario is highly ambitious for all countries. As a result, it requires drastic emissions reductions, approximately 7.6% annually globally (IPCC 2018; Höhne et al. 2020), and maintaining the cumulative emissions from 2020 until reaching carbon neutrality within a significantly reduced remaining global carbon budget, around 400 $GtCO_2$ (IPCC 2021). Although the energy sector emissions dropped in 2020 due to the COVID-19 pandemic, during 2021, the emissions rebounded due to the post-COVID-19 economic recovery (Friedlingstein et al. 2022). Therefore, the world seems far from achieving the 1.5 °C goal.

In this context, policy-makers from developing countries need analyses that asses mitigation goals under the prism of equity to propose arguments and strategies that align policies with the PA's global goals. The analysis in this research article is based on carbon budgets. We believe this is one way to strengthen transparency and promote environmental integrity. Formulating mitigation goals using the carbon budget and estimating the

cumulative CO_2 emissions that NDCs imply will reduce uncertainty on the aggregated effect of all NDCs. Moreover, it allows many developing countries, such as LATAM countries, to support their ambition arguments quantitively and based on equity and CBDR&RC principles, alleviating the increasingly limited capacity of the atmosphere to absorb CO_2 emissions without exceeding the agreed temperature goal.

Latin America is the region with the greatest contribution of the LULUCF sector to the total CO_2 emissions, which exceed 50% (Climate Watch 2022). Regarding development, indicators situate countries approximately on the world average, and there are no least developing countries in the regions.

The carbon budget allocated using the MCJ to Latin America from 2020 onwards amounts to 35.65 $GtCO_2$. This figure is 54% lower than the budget consumed from 1990 to 2019, and the percentage reduction is similar to what should be done globally. In the two considered scenarios, the estimate of the net cumulative CO_2 for 2020–2030 is below the carbon budget allocated for this region. Specifically, 77% of the carbon budget is consumed in the "NDC" scenario, and 58% is consumed in the "NDC w GLCF" scenario. Although both consumptions are above 55% (considered optimal), the "NDC w GLCF" scenario evidences that achieving ending with deforestation and reducing LULUCF emissions to zero would put Latin America in the 1.5 °C pathway. Moreover, the carbon budget consumption percentages might be reduced due to emissions reductions resulting from the policies stated but not quantified in countries' NDC.

As we evaluate the detail of LATAM countries, we observe three major groups:

- On the one hand, countries with very high deforestation rates are directly related to land change for extensive agriculture and livestock (Belize as an example). Generally, these countries have the worst economic and development indicators and have greater levels of inequality. It has been found that for these countries to stay within their carbon budget fair share, they must end deforestation and undertake a transition to land use management that provides local communities and indigenous peoples a sustainable model of life in harmony with the natural environment.
- On the other hand, we observe countries with fossil resources and economies based on exploiting these resources (for example, Venezuela). These countries should articulate policies to ensure a just transition of their energy sector to a low-emission development model.
- Finally, countries with net CO_2 far below the world average. All these countries could use a carbon budget higher than their historical emissions. Some of these countries have CO_2 removals in their LULUCF sector that compensate for the emissions from other sectors and good development indicators (for example, Uruguay). Others, on the contrary, are countries that still have significant development challenges for the future (Honduras, for example), and their remaining carbon budget should give them space to address their development needs. Therefore, gradually advancing toward a low-emissions economy.

Beyond the analysis presented in this article, we argue that the logic of the carbon budget should be intrinsic to the NDC. From the perspective of environmental integrity, assessing the cumulative net carbon emissions during the implementation period of every NDC can help estimate the contribution to the temperature goals (Matthews et al. 2020). Accordingly, in the effort toward a strengthened, transparent, and more ambitious implementation of the PA, countries must be able to set their mitigation goals by quantifying the carbon budget they will use. Such quantification will allow developing countries to

declare the atmospheric space they consider theirs fairly and guarantee the right to sustainable development and achievement of human rights. In addition, worldwide, it will allow monitoring of the consumption of the remaining global carbon budget compatible with the 1.5 °C goal, and, when the budget runs out, to make evident the enormous responsibility that will be put onto the future generations, a fact that constitutes a severe challenge for intergenerational equity.

Last but not least, the global health crisis caused by COVID-19 highlighted the need to establish international cooperation mechanisms and promote systemic transformations. These transformations will enable the world to face the climate change challenge, in line with what the IPCC has warned for many years. In this sense, it is fundamental to realize that these systemic transformations require a new political and economic ethos. Since the beginning of the industrial revolution, there has been an increase in the CO_2 concentration in the atmosphere that has no historical precedents. This is the cause of global warming that constitutes a severe threat to the viability of terrestrial ecosystems and the future of humanity (Guterres 2020). Some initiatives like the ones cited in this work, like the "Regulation on deforestation-free products" approved by the UE27 or initiatives that support local communities for forest ecosystem restoration, can help promote a paradigm shift for natural resources management in Latin America to ensure its population well-being and reduce inequalities.

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Declarations

Conflict of interest The authors declare no competing interests.

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